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ABSTRACT

A quantitative tool, the isoperm method, is described; it quantifies the effect of environmental factors of temperature (T) and percent relative humidity (%RH) on the anticipated useful life expectancy of paper-based collections. The isoperm method provides answers to questions of the expected lifetime of the collection under various temperature and relative humidity conditions, as well as a way to demonstrate the effects in quantifiable terms. The method is based on paper-strength loss associated with the chemical reactions of cellulose hydrolysis and oxidation. Relative, rather than absolute, rates of deterioration and paper permanence are employed. The deterioration-rate ratio can be controlled through changes in temperature and percent relative humidity, but it is not possible to change nonenvironmental factors, such as fiber type and so forth. The isoperm method is a step toward using quantitative analysis techniques and models to help make preservation-management decisions. Seven figures illustrate the discussion. (Contains 8 references.) (SLD)

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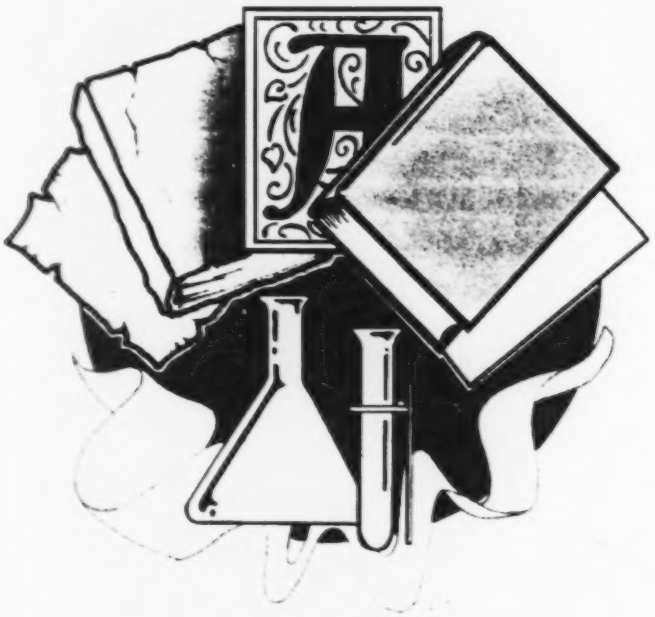
Isoperms

An Enviromental Management Tool



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Donald K. Sebera

June 1994

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Isoperms
An Environmental Management Tool

by
Donald K. Sebera
Consultant to the Commission on Preservation and Access

Published by
The Commission on Preservation and Access

June 1994

This paper addresses research needs arising from the Commission's Preservation Science Initiative, whose specific objective is to promote the development of communication among scientists and preservation administrators in order to solve problems of chemical properties of print media and set realistic priorities for continuing research. The long-range objective of the initiative is to enable librarians and archivists to apply these skills to a broad range of scientific and technical challenges accompanying the new media.

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The paper in this publication meets the minimum requirements of the American National Standard for Information Sciences-Permanence of paper for Printed Library Materials ANSI Z39.48-1992.

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Introduction

The challenges faced by the preservation administrator of a research library or archive in choosing among preservation alternatives are daunting. Typically faced with a varied collection and very limited budget, an administrator must make decisions and allocate resources among alternatives ranging from preservation microfilming to engineering a preservation environment of controlled temperature and relative humidity. Adding to the complexity and uncertainty of making these preservation decisions are nascent or near-future processes such as deacidification and paper strengthening as well as rapidly evolving technologies such as optical digital storage and format transfer that promise enhanced access. Any means of quantifying the preservation outcome of employing even one of these approaches would provide a powerful tool for the development of an overall preservation strategy. This paper describes one such quantitative tool — **the isoperm method** — that quantifies the effect of the environmental factors of temperature (T) and percent relative humidity (%RH) upon the anticipated useful life expectancy of paper-based collections.

This isoperm method provides ready answers to a large variety of questions related to environmental conditions such as: How much longer can I expect my collection to be preserved if I follow the recommendations of my conservation staff to change from the present storage conditions of 73°F and 50% RH to 60°F and 30% RH? What are the preservation consequences of allowing wider swings in temperature and percent relative humidity about the established set point conditions, since my HVAC (heating, ventilating, and air conditioning) consultant says tight limits are expensive in both capital and operating costs? Should I cycle between summer and winter storage conditions; if so, what risks and advantages are entailed? How can I convincingly show to curators, directors and funding agencies the preservation gains expected to result from modification and improvement of existing or construction of new storage facilities?

The basic theory underlying the isoperm method has been described in detail elsewhere (see *Sebera* in "Readings and References"). This publication is intended to serve as an aid in understanding the concepts so they may be used with greater confidence. My experience in presenting the isoperm concept has been that at first reading the science and mathematics appear complex and often intimidating. I urge continuing on to the applications where all the difficulties will disappear!

Finally, it should be noted that with appropriate modifications the method can be applied to other hygroscopic materials such as textiles, parchment, and so forth. In fact, it already has been extended to the preservation of film negatives. (*IPI Storage Guide for Acetate Film*, Image Permanence Institute, Rochester Institute of Technology, 70 Lomb Memorial Drive, Rochester, NY 14623-5604)

Scientific Basis

Deterioration of paper occurs by a variety of mechanisms and paths, one or more of which may predominate under specific circumstances. In a truly comprehensive approach, we must consider not only chemical deterioration but also biologically-induced degradation as well as physically-induced loss of strength resulting from handling and use at various frequencies and "intensity." The isoperm method is largely restricted to strength loss associated with the chemical reactions of cellulose hydrolysis and oxidation; conventional wisdom ascribed 90% or more of deterioration of paper to these two mechanisms.

Basically, the isoperm method arises from one idea: the rate of deterioration of hygroscopic materials such as paper is influenced by the temperature and percent relative humidity of its surrounding environment. The strength loss of paper resulting from the most common and important modes of chemically-induced degradation increases with increased temperature and moisture content. Conversely, lowering either or both temperature and moisture content of the paper reduces its rate of chemical deterioration and so increases the paper permanence. The isoperm method combines and quantifies the preservation effects of the two environmental factors, temperature and percent relative humidity, and presents the results in a readily comprehensible and usable graphical form.

What is at first sometimes confusing but is essential to an understanding of isoperms is that *relative* rather than *absolute* rates of deterioration (and paper permanence) are employed. That is, if r_1 and r_2 are the (absolute) rates of deterioration of a specific paper under two sets of temperature and relative humidity conditions we shall *not* deal with r_1 and r_2 individually but only with their ratio r_2/r_1 which measures the relative change in the deterioration rate resulting from the change in environmental conditions. To illustrate, suppose a certain decrease in temperature and/or relative humidity results in the initial deterioration rate, r_1, dropping to a new lower rate, r_2, such that $r_2/r_1 = 0.5$. This ratio carries the implication that all papers subjected to this change in environmental conditions will have their rates of deterioration cut in half. The rate reduction would be the same twofold value irrespective if a paper was short or long-lived. A paper which, for example, reached a given state of embrittlement in 45 years under the initial set of conditions would, because its rate of deterioration was halved, attain the same state of brittleness in 90 years under the new conditions. Similarly a paper with a 200 year life expectancy would see its permanence extended to 400 years.

It is the deterioration rate *ratio* that the preservation manager can control through changes in the temperature and percent relative humidity of the collection storage areas; it is not possible to change non-environmental factors such as fiber type, fiber length, degree of beating of the pulp, basis weight, thickness, and so forth, all of which influence the absolute rate of deterioration of a given paper.

The time a paper takes to reach a given level of residual strength is, of course, inversely related to the rate of deterioration. This life expectancy, which we shall refer to as permanence, rather than the deterioration rate, is the more apt and useful term to describe the effect of environment. The ratio of the two permanence values, i.e., the relative permanence, is mathematically the inverse of the deterioration rate ratio:

$$\frac{P_2}{P_1} = \frac{1}{r_2/r_1} = \frac{r_1}{r_2} \qquad (1)$$

Here, as in the earlier illustrations, a precise definition of permanence has not been given; it is only essential to understand that it denotes the time required to attain some specific state of deterioration or residual strength. In other contexts it has been found useful to define permanence as the time required for a paper to drop to a strength of 1 MIT double fold at a 0.5 kg (kilogram) load, but other measures may be used.

Effect of Relative Humidity

Water is important as a reactant or catalyst in many chemical reactions. As already stated, the rate of deterioration of cellulose by hydrolysis is directly related to the moisture content of the paper which in turn is directly related to the percent relative humidity (% RH) of the atmosphere in which the paper is placed. We may summarize the effect of % RH as: the greater the % RH of the environment, the greater the moisture content of the paper, the higher the moisture content of the paper, the greater the hydrolysis deterioration rate of the paper, the faster the paper deterioration, the shorter the life expectancy (permanence) of the paper. These ideas can be summarized mathematically in the equation:

$$\frac{r_2}{r_1} = \frac{H_2O \text{ concentration}_2}{H_2O \text{ concentration}_1} = \frac{RH_2}{RH_1} = \frac{P_1}{P_2} \qquad (2)$$

where RH is the percent relative humidity of the environment in equilibrium with the paper.[1] Equation *2* provides a good quantitative approximation for deterioration rates (and permanence) in the practically important range of 30-65% RH; outside this range papers show increasing deviations from Equation *2* behavior. Thus, by controlling the relative humidity we can affect the paper permanence and, within the middle of percent relative humidity values, we can quantitatively estimate the effects with good accuracy.

Effect of Temperature

It is widely recognized that most chemical reactions proceed at a faster rate as the temperature is increased. Many of us are familiar with the rule of thumb stated in elementary chemistry courses that "chemical reaction rates double with each 10°C increase in temperature." However, in truth, each reaction displays a different specific "sensitivity"[2] to temperature changes increasing by more or less than the factor of *2*. Physical chemists have developed a theory of chemical reaction rates (Transition State Theory) that can accurately describe the effect of temperature changes on reaction rates. Their equation for the relative rate of reaction at two (Fahrenheit) temperatures T_1 and T_2

$$\frac{r_2}{r_1} = \left(\frac{T_2+460}{T_1+460}\right) 10^{-.394\Delta H^*} \left(\frac{1}{T_2+460} - \frac{1}{T_1+460}\right) \qquad (3)$$

incorporates a constant, the enthalpy of activation, ΔH^*, a thermodynamic function that quantifies the sensitivity of a specific reaction to temperature changes.[2] ΔH^* has a specific value that may be experimentally measured for each paper. Most (of a limited number) of such experimental

[1] We should recognize that Equation *2* applies to papers in equilibrium with their environment. Individual closed books and tightly packed manuscript boxes are slow to respond to environmental % RH changes. Though their outside edges may equilibrate in minutes or hours, it often requires months for the moisture content in the center of a book to reach its equilibrium value for a specific % RH. For convenience we shall assume equilibrium with atmospheric conditions for both temperature (a very good approximation) and relative humidity (good only over relatively long time intervals).

[2] An older, less accurate theory expresses sensitivity to temperature change as the Arrhenius activation energy, E_{act}. The enthalpy of activation is slightly larger numerically than E_{act}.

measurements place ΔH^* in the range of 20-35 Kcal (kilocalorie) with a value of 30-35 Kcal providing a very good approximation for most preservation applications.[5]

Up to this point we have examined the effects of changing temperature and percent relative humidity individually in both qualitative and quantitative terms. What remains is to combine their effects into a single equation that will be transformed into the graphical isoperm formulation.

Combined Effects of T and % RH

If changes in both T and % RH are simultaneously made to a paper's environment the resulting deterioration rate will reflect their combined effects. This combined effect on the rate ratio is the product of the individual ratio effects. Therefore, by multiplying Equations 2 and 3 we get the overall effect on deterioration rates:

$$\frac{r_2}{r_1} = \left(\frac{RH_2}{RH_1}\right)\left(\frac{T_2+460}{T_1+460}\right) 10^{-394\Delta H^* \left(\frac{1}{T_2+460} - \frac{1}{T_1+460}\right)} \qquad (4)$$

and on permanence:

$$\frac{P_2}{P_1} = \left(\frac{RH_1}{RH_2}\right)\left(\frac{T_1+460}{T_2+460}\right) 10^{+394\Delta H^* \left(\frac{1}{T_2+460} - \frac{1}{T_1+460}\right)} \qquad (5)$$

Using the appropriate environmental values for the T's and RH's and an estimated or experimentally determined value for ΔH^* these equations can be evaluated algebraically to obtain a quantitative evaluation of permanence changes.

Definition of Isoperm

Algebraic computations using Equation 5 would be time consuming if not daunting to all except those with mathematical interests and skills. The equation would be more readily usable if cast in graphical form. The next paragraph, which describes this transformation, is the key to the isoperm method.

Consider a paper at equilibrium with some initial conditions of temperature and relative humidity that determine its rate of deterioration and permanence. Now let us increase the relative humidity to a higher value; if the temperature is unchanged, the rate of deterioration will increase. However, if we reduce the temperature by *exactly the right amount*, the resulting temperature induced rate decrease *will exactly compensate for* the relative humidity induced increase so the overall deterioration rate (and permanence) is unchanged from that at the initial environmental conditions. We can make another change in relative humidity (or temperature), and another temperature (or relative humidity) can be found that again will exactly compensate for the new relative humidity (or temperature) induced permanence change. There is, of course, an infinite set of such paired T and % RH conditions, all associated with the same permanence value. These paired values when plotted on a graph of T and % RH as axes generate a line. This line of constant permanence (isopermanence) is defined as an *isoperm*. Figure 1 is such a graph.

[5] This equation, with appropriate H^* values, can be applied to paper properties other than strength. For example, the rate of thermally induced color formation in paper, i.e., rate of discoloration, can be described using a H^* value of *ca.* 20 Kcal.

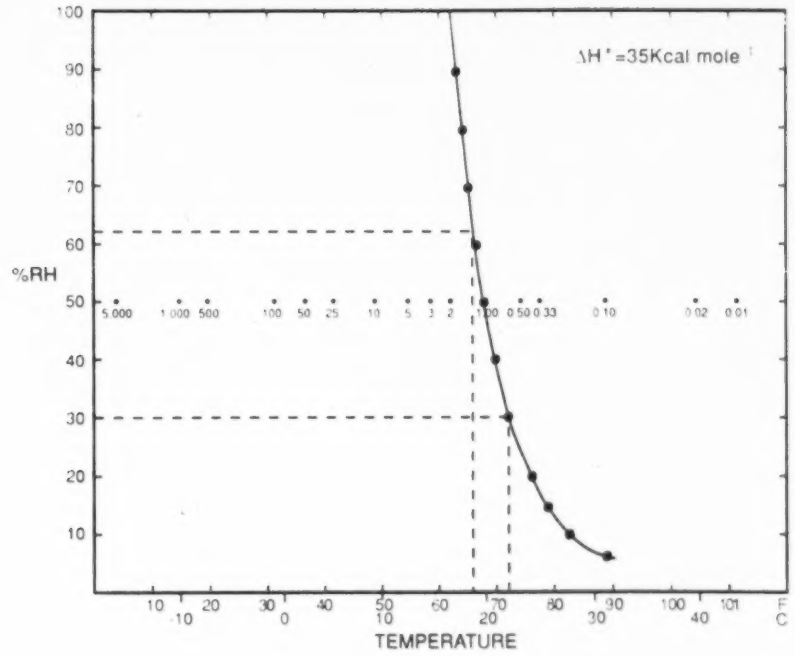

Fig. 1. Construction of an Isoperm. Paper permanence value at 68° and 50% RH is assigned a relative value of 1.00. Other temperature and relative humidity conditions which also have permanence value of 1.00 are plotted and joined to yield an Isoperm of value 1.00. Valules of permanence at 50% RH and various temperatures are shown.

A 68°F temperature and 50% RH is arbitrarily selected as the initial or reference environmental state of permanence, P_1. Any other T and % RH values could have been selected as a reference state but 68°F/50% RH is reasonably close to common storage conditions and so can serve as a useful basis or standard for comparison with other conditions. The other paired points, and thus the overall shape of the isoperm, is established by computation from Equation 5. In the calculation, a value of 35 Kcal is used for ΔH^* and the relative humidity is changed by 10% increments; the temperature which keeps the permanence equal to that at 68°F/50% RH is calculated and the paired points are connected. The resulting isoperm line is labelled 1.0 since it shows conditions where all P_2's equal P_1, as the relative permanence is unchanged $P_2/P_1 = 1.0$.

What does the isoperm value of 1.0 on the graph mean? For now, as a first illustration we can say that if a paper had a 45 (or 90 or 300) year life expectancy at 68°F/50% RH it will have the same permanence (45, 90 or 300 years) at any environmental conditions along that line — at 72°F/30% RH or 66°F/62% RH for example.

Figure 1 also displays the temperature (at 50% RH) corresponding to permanence values greater and less than 68°F/50% RH. The isoperm values of 5.0 and 0.33 at 54° F and 78° F respectively mean that the paper of 45 years permanence at 68°F would require 225 years to attain the same state of deterioration at 54°F, but only 15 years to attain the same state of deterioration at 78°F.

Figures 2 and 3 display a completed array of isoperms for ΔH^* values of 25 and 35 Kcal drawn for selected relative permanence values. Other isoperms can be calculated from Equation 5 or are easily estimated by interpolation. It is evident that while the two diagrams are very similar, the 35 Kcal graph shows a greater "sensitivity" to temperature changes. Taken together they both show the importance of using the appropriate ΔH^* for a collection. It should be

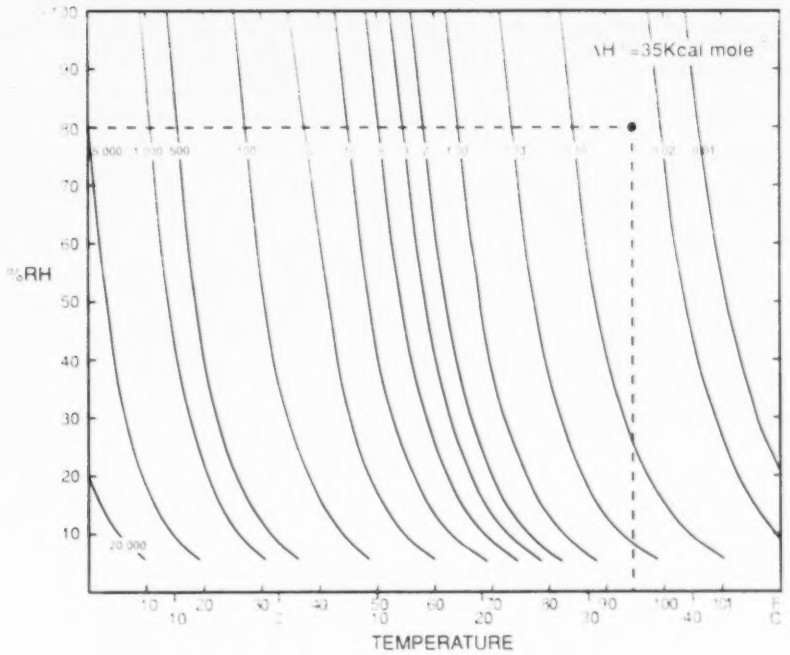

Fig. 2. Percent relative humidity versus temperature Isoperm diagram. Permanence values are calculated for $\Delta H^* = 35$ kcal relative to paper at 68°F and 50% RH taken as comparison standard (permanence equal to 1.00). Relative permanence at 95°F and 80% RH is ~0.03.

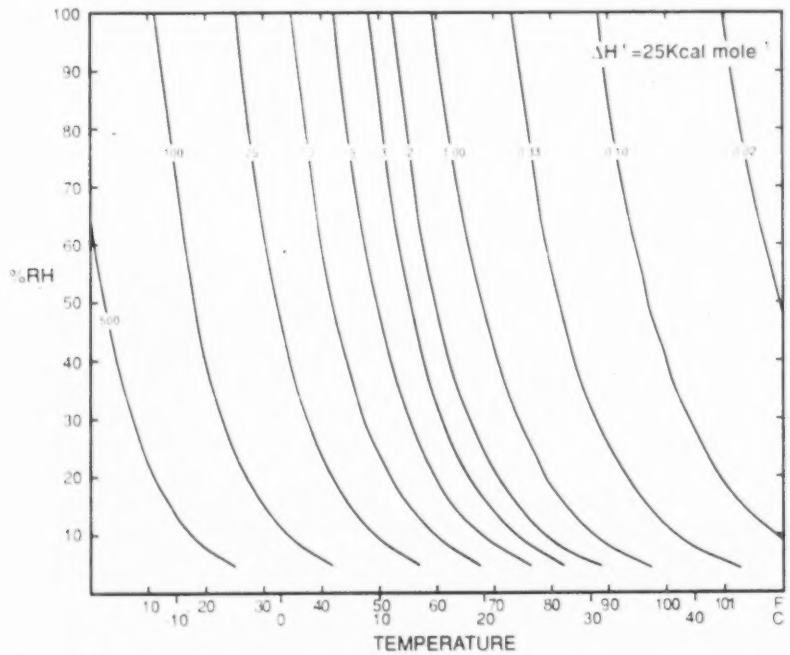

Fig. 3. Percent relative humidity versus temperature isoperm diagram. Permanence values are calculated for $\Delta H^* = 25$ kcal mole^{-1} relative to paper at 68°F/50% RH taken are reference standard (isoperm equals 1.00).

noted that for the narrow range of T and % RH commonly encountered in research libraries and archives, the uncertainty introduced is relatively small and probably insignificant for most practical purposes.

Applications of % RH *vs.* T Isoperm Diagrams

We now have reached the point where we have all the elements necessary to utilize isoperm diagrams in answering questions like those posed in the Introduction. The remainder of this paper will explore various scenarios to illustrate how % RH *vs.* T isoperm diagrams can assist in making preservation management decisions.

As a simple illustration consider the scenario: A collection of relatively short-lived papers (perhaps newsprint paper estimated to have a permanence of 45 years under 68°F/50% RH storage conditions) must be moved to make room for a more valuable collection. It is suggested that the papers be temporarily (1-2 years) placed in storage in a utility tunnel. The site chosen is next to a slow-leaking steam line, and the papers will be in an environment of 95°F and 80% RH. What are the preservation consequences of making this move? Referring to Figure 2 we see that the 90°F/80% RH conditions lie between the 0.10 and 0.02 isoperm line — we can estimate a 0.03 isoperm value. We conclude that under the new storage conditions the collection's life expectancy would be reduced to about 3% of the permanence at the initial conditions — that is, about 16 months. Even given the uncertainties inherent in the estimation[4], one or two years of this "temporary" storage would destroy the collection! The preservation manager is now armed to reject the proposal and suggest an alternative.

Diagrams plotting %RH *vs.* T can be of value even in the absence of an isoperm application. Very often discussions of preservation issues with non-specialists are more effectively conducted through the use of graphs and other visual aids. For example, the area on Figure 4 labelled TOO INFLEXIBLE quickly communicates the idea that because papers stored at low relative humidities (say less than 30% RH) with their low attendant moisture content, are, whatever their strength, so inflexible as to be prone to damage in handling. The graph quickly communicates the idea that papers should never be exposed to the labelled area conditions. Similarly, high relative humidities are conducive to mold formation and foxing of paper. The area labelled MOLD indicates environmental conditions to be avoided if these forms of biological deterioration are to be prevented.[5]

Figure 5 shows an area labelled TOO RAPID DETERIORATION; it expresses a specific management decision. A policy decision has been made by the preservation manager or director or even at the board of trustees level that no item in the collection should ever (whether in storage, exhibition, shipping, on loan, and so forth) be exposed to environmental conditions at which it will deteriorate at a rate (say) three times greater than that of the institution's normal storage conditions of

[4] The example lies outside the most accurate % RH region of 30-65% so is subject to a greater uncertainty. In fact the isoperm method probably underestimates the effect of % RH and so the lifetime will probably be even shorter than the estimate.

[5] In these two, and other situations described, the conditions given are for illustrative purposes only. The exact conditions under which, for example, mold will form is dependent on many factors so the 65% RH value is realistic but not restrictive.

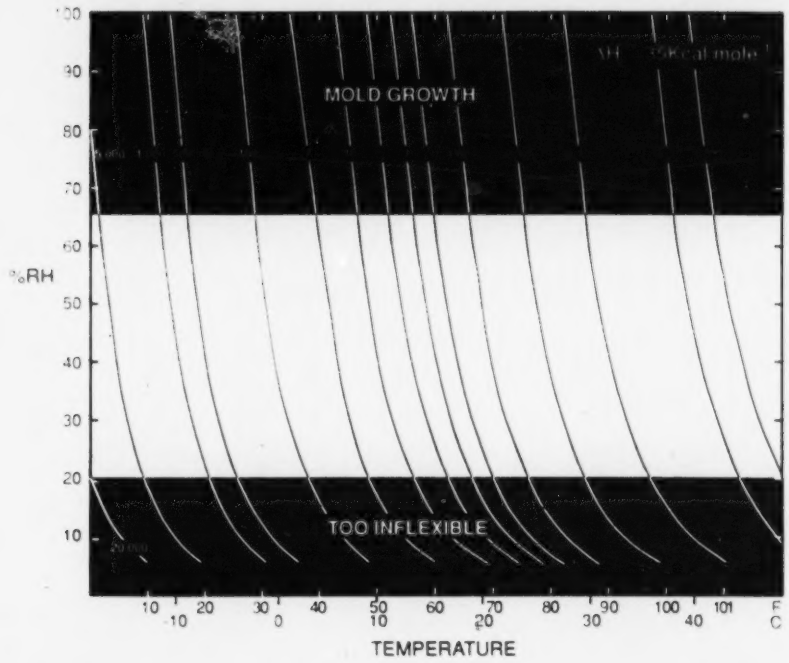

Fig. 4. Percent relative humidity versus temperature Isoperm diagram displaying environmental conditions unsuitable for paper. Relative humidities greater than 65% subject paper to hazards of mold growth and foxing; values less than 20% RH reduce paper flexibility to potentially hazardous levels.

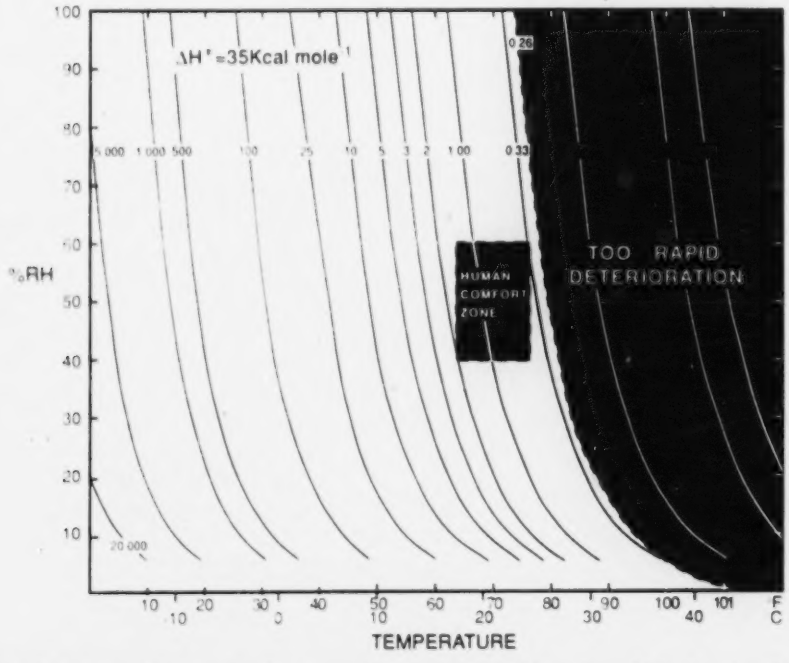

Fig. 5. Isoperm diagram displaying environmental conditions for which deterioration is so rapid that paper permanence is one-quarter or less than conditions of 68°F and 50% RH. Also shown are relative permanence values associated with environmental conditions associated with human comfort.

70°F/50% RH (an isoperm value of 0.79). The preservation manager can construct an isoperm at the 0.26 value; all exposure of objects to conditions to the right of 0.26 isoperm (the labelled area) are barred by the policy. A % RH *vs.* T isoperm with the restricted area(s) indicated could be made part of any loan agreement between institutions.

Figure 5 also displays an area labelled HUMAN COMFORT ZONE. HVAC engineers, architects and the Occupational Safety and Health Administration (OSHA) have defined a range of temperature and relative humidity conditions that provide acceptable comfort and safety for humans working in or occupying a building.[6] Such a relatively wide range of conditions allows libraries and archives with good environmental control systems to select and maintain specific conditions within these limits. The ultimate choice often is established by the director after consultation with HVAC engineers, system operators, perhaps an architect, various staff members and union representatives. The director will obtain information about capital and operating costs and maintenance expenses for various conditions; there may be a history of complaints from public and staff about hot, cold, clammy, and other conditions; and the architect may indicate potential structural damage from excessively high percent relative humidity conditions. What should the preservation manager's contribution and recommendations include?

The earlier discussion of potential mold growth and damage from paper (and book structure) inflexibility clearly would be relevant, but the choice made within the range of possible conditions can profoundly affect the preservation of the collection. In Figure 5 the least favorable conditions are associated with the upper right hand corner at 76°F/60% RH; this corresponds to an isoperm value of 0.33. The conditions most conducive to preservation are found in the lower left corner at 64°F/40%, a 2.0 isoperm value. The human comfort zone thus encompasses a six-fold range in collection permanence. This relationship can be easily communicated to the director and advisors and used to support the recommendations of the preservation manager to establish low % RH, low T conditions.

Figure 6 displays what are by now fairly obvious applications of the % RH *vs.* T isoperm diagrams and one much less obvious application.

An arbitrarily selected point at 50°F/45% RH is shown surrounded by a dashed box. This represents the preservation conditions with the environmental control system with 50°F/45% RH as its set point and ±3°F and ±5% RH its control limits. The isoperm running through the set point is 9.6, and the isoperms are 6.0 and 15.7 at the excursion limits of 53°F/50% RH and 47°F/40% RH respectively. Thus the selection of these values for the set point and excursion limits results in a 15.7/6.0 = 2.6 factor in permanence. Narrowing the excursion limits will reduce the range in permanence — undoubtedly at higher capital and operating costs — but extending the limits too widely will ultimately allow conditions of an excessively high deterioration rate.

The selection of set points and operating limits and their accompanying influence on cost:benefits ratio is however somewhat more complicated than so far presented. Looking at a % RH *vs.* T isoperm diagram we see that, except at very low % RH's, the curves fall very steeply, which implies deterioration rate is much more sensitive to T than to % RH changes. In the example chosen of 50°F/45% RH, we can use Figure 5 (or for greater accuracy, Equation 5) to show the isoperm value changes by a factor of 1.13, i.e., 13% for each degree of temperature change but only by a factor of 1.02 (or 2%) for a one percentage point change in % RH. When the chemical deterioration factor is taken alone, the preservation manager will probably decide to devote more resources to temperature control than to relative humidity control. This judgment is supported by the observation made earlier that the moisture content of books responds more slowly to environmental changes than does the temperature of books. Thus all but the outermost edges of a book would be at equilibrium with the long-term average relative humidity.

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[6] The area shown is reasonably representative of a human comfort zone but once again it is illustrative only and should not be used for design or compliance purposes.

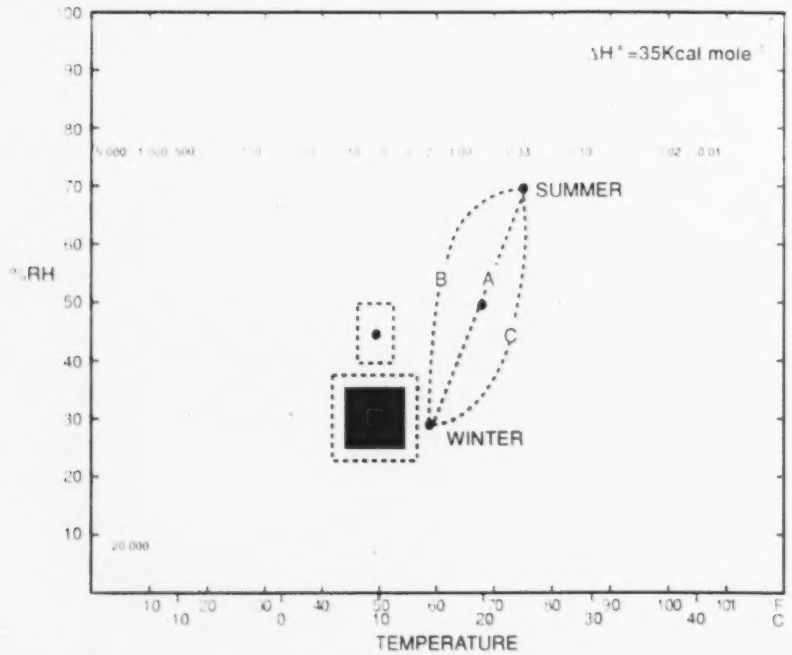

Fig. 6 Isoperm diagram displaying environmental set points and tolerance limits. Set points are shown as •; set ranges are indicated by ■; tolerance limits are indicated by surrounding broken lines. Also shown are permanence consequences of annual cycling between winter (60°F, 30% RH) and summer (80°F, 70% RH) environmental conditions.

Figure 6 addresses a question posed in the Introduction suggesting that for economic and/or operational reasons two set points should be established for the collection. The first, for winter months, is of lower % RH and T; the second, for summer months, has a higher % RH and T. The three dashed lines connecting the two conditions represent the environmental path taken in transitioning between them. Appropriate choices for the two conditions are anticipated to give a satisfactory intermediate average isoperm value that satisfies the preservation requirements. However, the preservation consequences of annual cycling need to be examined in considerable detail since cycling is more complex than it first appears.

Suppose the non-cycling environment is taken as 68°F/50% RH and the (unrealistically large but useful for illustrative purposes) annual cycling is ±8°F and ±20% RH. The summer and winter conditions therefore are 76°F/70% RH and 60°F/30% RH. These conditions have isoperm values (estimated from the % RH *vs.* T isoperm diagram or more accurately calculated from Equation 5) of 0.29 and 4.3 respectively. If, for simplicity, we assume that the collection spends six months in each environment, i.e., the conditions are abruptly changed from winter to summer and the collection instantaneously equilibrates to the new conditions, we can now ask the question, "how will a collection cycled over the 12-month period fare compared with a constant 68°F/50% RH?"

Our first observation is that summer conditions result in a deterioration rate 1/0.29 = 3.5 times greater than the constant conditions, while winter conditions yield a 4.3/1.0 = 4.3 factor decrease in deterioration rate. From this we might (incorrectly!) conclude that (apart from any potential cost savings) cycling results in greater preservation of the collection. This incorrect assessment is apparently reinforced by taking the average of the two isoperms, (4.9 + 0.29)/2 = 2.3, suggesting enhancement of permanence by a factor greater than 2.

The key to a *correct* understanding of cycling effects is best seen by an automobile analogy. Suppose a car is driven for two hours in two different ways: the first, for two hours at a constant speed of 50 mph; the second, one hour at 4 times the 50 mph speed and one hour at 1/4th the 50 mph speed. How many miles (how much paper deterioration occurs) in the two scenarios? In the constant speed case we have 2 x 50 = 100 miles, but in the second we have 1 x 4 x 50 + 1 x 1/4 x 50 = 212.5 miles. In a similar way, the approximately 4x greater deterioration in the six summer months is not compensated by the six winter months of 1/4th rate of deterioration and in fact (using our automobile analogy) we may anticipate approximately twice the deterioration.

The summer and winter seasonal isoperm values of 0.29 and 4.3 may be used to calculate an annual average deterioration rate and a (correct!) average isoperm value by recalling that relative deterioration is the inverse of relative permanence or isoperm value. Thus the summer and winter deterioration rates are 1/0.29 = 3.5 and 1/4.3 = 0.23, giving an annual average deterioration rate of (3.5 + 0.23)/2 = 1.9 which in turn corresponds to a 1/1.9 = 0.5 isoperm value. Calculation of average isoperm values for other seasonal environmental conditions and time periods follows this same "inverse-inverse" method of averaging.

This examination of cycling has much broader implications for the preservation of collections since it shows that any departure from moderate fixed to rapid deterioration conditions, even for relatively brief periods of time, results in more deterioration than might first be expected. Recalling our earlier example, even one short exposure of the collection to the hot, damp, leaking steam pipe environment greatly reduces its expected useful life.

Returning to Figure 6 allows us to develop a transitioning strategy between the two seasonal conditions that can to some extent mitigate these cycling effects. Path A is like the example discussed, except the transition takes place over a period of weeks or months with the % RH and T each changed at a constant rate. Path B also moves uniformly over time, but in going from winter to summer and summer to winter conditions the rate of temperature change is varied so that for much of the year the collection remains in the high isoperm values thereby enhancing permanence. In going from summer to winter conditions we lower the temperature as rapidly as possible and allow the relative humidity to catch up more slowly; going from winter to summer is the reverse — we keep the collection cold as long as possible then rapidly raise the temperature. Path B is also the one most easily achieved in practice since as already noted, book temperatures respond more rapidly to environmental changes than does book moisture content. Path C is one which clearly results in moré deterioration than A or B.

Figure 6 also displays a rectangular block surrounded by a dashed line box. This, rather like the depiction of a human comfort zone, is the representation of the range of T and % RH conditions specified as a standard. A library can meet the standard by establishing a set point anywhere in the solid outlined box with the dashed line indicating the maximum T and % RH departure allowed from the set point. The preservation implications of a specific standard can be drawn by following the procedures already described.

One of the most difficult problems facing the preservation manager is the selection of set points, operating ranges and cycling patterns for the collection environment especially where selections must be made from alternative (and sometimes even conflicting) standards. The following scenario describes such a situation with an analysis that illustrates the role isoperms can play in understanding and quantifying various implicit preservation issues.

A group of expert conservators, after considerable deliberation and using the available scientific information as well as their years of practical experience, proposes the set of storage conditions displayed in Table 1. Several broad distinctions and categories were established: Bound materials were distinguished from unbound; a Preservation Collection was identified as distinct from the General Collection. Distinct diurnal and annual environmental conditions were allowed as was specification of the rate of change between them. Very low temperature storage conditions were

specified (presumably for special collections). Alternative standards were proposed to allow costs and other practical considerations to be weighed in the ultimate choices and decisions. The challenge to the preservation manager is to understand in detail what is being proposed and how to implement the appropriate standard.

A. SET POINT RANGES

GENERAL COLLECTION				PRESERVATION COLLECTION			
BOUND RECORDS		UNBOUND RECORDS		BOUND RECORDS		UNBOUND RECORDS	
Temp., °F	% RH	Temp., °F	% RH	Temp., °F	% RH	Temp., °F	% RH
65-70	40-55	65-70	25-35	55-65	30-40	55-65	25-30
				45-55	25-35	45-55	25-30
				35-45	20-25	35-45	20-25
				0	20-25*	0	20-25*

*Hermetically sealed at this % RH before reducing temperature to 0°F

B. SET POINT TOLERANCES

GENERAL AND PRESERVATION COLLECTIONS		
DIURNAL	±2°F	±3%RH
ANNUAL	±2°F	±5%RH
MAXIMUM CHANGE PER MONTH		

Table 1. Environmental conditions illustrative of those proposed for storage of paper documents.

Even a few minutes spent examining Table 1 raises a number of questions and issues not easily addressed by the proposal itself: How "good" are the various proposed standards for the General Collection? How do they relate to one another in permanence value? On what basis can we choose one over another? The environmental conditions proposed for the Preservation Collection appear "better" but how much better? Substantially? Significantly? Since the distinction between bound and unbound material probably expresses concerns about stresses by and on binding structure, do the standards show differences that consistently reflect structural considerations? Is it T or RH that the standards suggest impacts most on binding structures? Can one even begin to estimate a cost:benefit ratio for the alternative standards? Are any of the standards compatible with comfort and safety requirements of staff and users? The preservation manager undoubtedly can raise many more questions and issues to address before recommending a course of action.

Figure 7 displays the different standards proposed in Table 1 on a %RH *vs.* T isoperm diagram. In the figure, some of the relationships and the various proposed standards are immediately evident and answers to the previous questions clearly depicted: Unbound materials can be kept at lower relative humidities although some standards propose identical (i.e., in the diagram) overlapping, storage conditions. The General Collection, whether bound or unbound, is stored under less favorable conditions than the Preservation Collection; in fact one might ask if the conditions are adequate since the maximum bound General Collection isoperm has a 1.8 value. On the other hand, some Preservation Collection isoperm values are quite large — storage at 30°F/20% RH has a 150 isoperm value. Under these conditions, a paper with a lifetime of 75 years at 68°F/50% RH would be expected to survive for more than 10,000 years. Even more questionable, perhaps, is the standard proposing storage at 0°F/25% RH. Here even an extremely short-lived paper of say 5 years would be expected from the isoperm value of 15,000 to survive for 75 millennia! Even allowing for major uncertainty in the isoperm value because of such extreme pressure on the assumptions and approximations in the isoperm method, it is questionable whether such storage conditions can be economically justified and whether we know enough about sealed storage conditions and how they may promote deterioration.

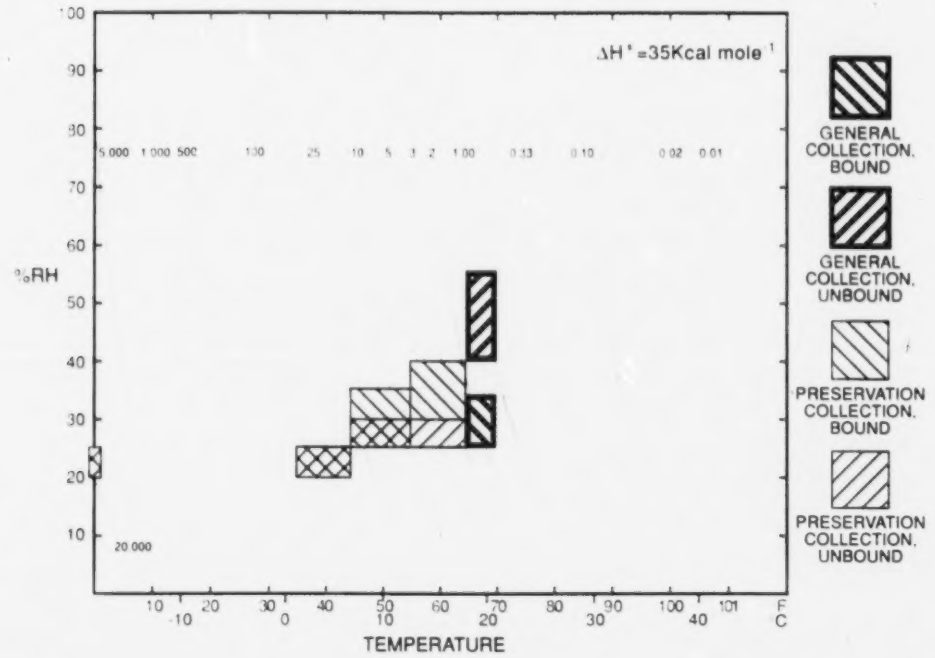

Fig. 7. Isoperm diagram displaying set points and ranges illustrative of those proposed for paper document storage (Table 1).

The % RH *vs.* T isoperm diagrams do not, of course, ***make*** decisions but Figure 7 amply illustrates how they can, by their convenience and quantitative aspects, provide information to assist preservation managers in making decisions.

From the applications presented and scenarios considered, it would be easy to presume that isoperm concepts are applicable only to institutions with large staffs and sophisticated HVAC systems. In fact, the isoperm method may be of even greater value where staffs are small, such systems are lacking and environmental control is more difficult to achieve. Examples may range from the very small, locally supported historical society with some holdings of books, letters and newspapers, which is open only in the summer and is closed and unheated in the winter months, to a medium size or even large library or public records office with adequate (or perhaps excessive) heating in the winter and open doors and windows in the summer. In some cases, a small staff may mean the director wears the preservation manager's hat as well as many (perhaps all) others. How can isoperms help in these cases?

Perhaps the greatest barrier to improvement in the preservation environment is the inability to assess the current preservation state and to ascertain whether and how changes can improve that state. Knowledge of the preservation consequences (gained from isoperm diagrams) of making changes of only a few degrees in temperature can provide the additional motivation to make these and additional changes.

Undoubtedly the first step (if it has not already been done) is to measure temperature and percent relative humidity at various locations in the collections throughout the year. If the T and % RH data are plotted on an isoperm diagram (even as they are being collected) patterns of permanence values will develop. Large pattern differences between summer and winter conditions certainly will appear. There probably will be different patterns for significantly different areas

— near windows when opened and closed, near and remote from heating ducts, areas in shade and direct sunlight, south and west facing rooms compared with those facing east and north, different floor levels and attic and basement — are some general examples.

These plotted diagrams first of all provide a quantitative estimate of the current preservation status that may be compared against accepted standards. There may be some pleasant as well as unpleasant surprises. What actions can be taken to improve conditions is very situation specific, but some possibilities are: If it is found different rooms fall into different isoperm value regions it may be possible to shift temperature and relative humidity sensitive materials in the collection to rooms of greater isoperm value. Experiments can be done changing the pattern of window opening and closing, using awnings or sunlight shields, or drawing in cool night air with small window or "whole house" fans. The % RH and T results of these experiments plotted on an isoperm diagram can measure how much, if any, improvement in conditions was achieved. Use of the "whole house" fan at night or a small window type air conditioner, while not causing drastic changes of environment, may sufficiently reduce peak summer temperatures to produce (as seen earlier in annual cycling) a substantial preservation impact.

The condition survey isoperm diagrams, together with diagrams showing the effects of changes already made and what remains to be done, can be useful tools for obtaining additional support from local benefactors and foundations. Quantitative knowledge of the preservation status of the collection can provide a powerful motivation for action.

Numerical Values of Isoperms

It is appropriate at this point, now that the isoperm concept and some of its applications are understood, to examine in greater detail the factors which affect the numerical values of isoperms. The values generated thus far arise from choices of parameters and assumptions which, though useful for expository and illustrative purposes, may not be best for a specific collection. The following discussion illustrates how the isoperm assumptions (and so Equations 4 and 5 and the resultant % RH vs T isoperm diagrams) can be modified to incorporate new experiential information.

In the development of Equation 4 the dependence of deterioration rate on % RH was taken as linear and so the relative deterioration rate at two different % RH's is also linear. This is expressed mathematically in Equation 2 as raising the ratio of % RH's to the first power.

$$\frac{\text{rate of deterioration}_2}{\text{rate of deterioration}_1} = \frac{\%\,RH_2}{\%RH_1} = \left(\frac{RH_2}{RH_1}\right)^{1.00} \qquad (2A)$$

Some studies suggest that the deterioration rate is more sensitive to relative humidity than a linear dependence. For some papers in the middle ranges of % RH (30-60%) the dependence may be the power 1.4 rather than 1.0, thus the relative humidity component of Equation 5 would be the following.

$$\left(\frac{RH_1}{RH_2}\right)^{1.4} \quad \text{rather than} \quad \left(\frac{RH_1}{RH_2}\right)^{1.0}$$

The consequence of this change to the % RH vs T isoperm diagram would be to somewhat decrease the steepness of the slope of each isoperm line. We can estimate the magnitude of this effect at the %RH limits likely to be encountered in a collection controlled by and HVAC system (30-60% RH). The relative humidity contribution to the isoperm value would become

$$\left(\frac{60}{30}\right)^{1.4} = 2.6 \text{ rather than } \left(\frac{60}{30}\right)^{1.0} = 2.0$$

A change in value of this magnitude, i.e., 30%, while itself significant, may not affect a management decision based upon life expectancy differences of 200-300% or more.

More significant is the selection of an appropriate value of ΔH^*. As can be seen by comparing Figures 2 and 3, the difference between isoperm values for ΔH^*'s of 25 and 35 Kcal is substantial, especially for large temperature changes. The 35 Kcal value used in the examples was selected in part because it resulted in larger, more easily recognized differences while still being a value appropriate to many papers. The precise choice of a particular value ΔH^* will unquestionably depend in considerable part upon the specific papers in the collection as well as the manner in which they are housed (bound books, boxed manuscripts, newspapers, and so forth). For some of these collections at least, a ΔH^* value of 25 Kcal may be more appropriate and the % RH vs T isoperm diagram of Figure 2 may be more appropriate than Figure 3. The numerical values of isoperms discussed in the illustrations of stated paper should *not* be taken as necessarily the best for all situations. The preservation manager, before making decisions and committing expenditure of funds, should seek the advice of experts or carefully review the most recent literature. Indeed, the need for more specific temperature dependency data has been recognized by the preservation community and proposals have been made to conduct such studies to obtain more information.

While awaiting these studies and expert advice, the preservation manager can explore the preservation consequences using both the 25 and 35 Kcal isoperm diagrams. Such a comparison will show the differences in isoperm value associated with this range of ΔH^* values and suggest whether the differences are large enough to significantly affect the manager's decision.

Another even more cautious and conservative approach would be to utilize the 35 Kcal % RH vs T diagram for isoperm values below 1.0 and the 25 Kcal diagram for isoperm values above 1.0. This would have the effect of increasing (exaggerating?) the anticipated harmful effects of higher temperatures, and decreasing (under estimating?) the life expectancy consequences of lowering temperatures. Though such approximations may be sufficient to provide the basis for a management decision, they cannot, of course, provide the confidence inspired by developing and using the isoperm values most appropriate to a given collection.

Summary

This paper started with a brief review of the chemical and physical factors associated with the deterioration of paper. It then combined them with several assumptions approximations and definitions to obtain an isoperm — a quantitative graphical measure of relative permanence. Graphs were then used to describe and analyze a number of situations and systems. The aim of the paper is to provide a language or device that aids understanding and communication of preservation issues and assists in making preservation management decisions.

Studies to refine the isoperm method by measuring ΔH^* values for larger numbers and types of paper are underway. More detailed information about the relationship of relative humidity to moisture content and deterioration rate is being gathered as is information on the effects of relative humidity and temperature cycling. The extension of the isoperm concept to other media such as magnetic tape, textiles, and film is being undertaken; as mentioned earlier, application to film already has been made by the Image Permanence Institute.

An earlier analysis of the effects of deacidification and paper strengthening upon paper permanence is also relevant. Deacidification, like environmental control, fundamentally produces life extension by reducing the rate of chemical deterioration. The analysis not only quantifies the consequences of deacidification but describes the powerful synergistic effects of combining different modes of reducing the deterioration rate. for example, a 3x reduction from environmental change combined with a 4x life extension from deacidification of acidic papers results in a 12x increase in permanence.

In a more speculative vein, it appears that preservation and preservation management may be entering a stage of development when quantitative analysis techniques and models can be used to help make preservation management decisions. We may be seeing the formation of a discipline or sub-discipline with the term *Preservation Metrics* — rather like Econometrics in economics. Isoperms may be one of the measures that will be found useful in preservation metrics.

Readings and References

Arney, J. and Novak, C., *Technical Association of Pulp and Paper Industry*, 65, 113 (1982). This and another earlier paper by Arney provide an introduction to some of the detailed chemistry of paper deterioration.

Bansa, H., and Hofer, H., *Das Papier*, 34, 348 (1980) . An early paper of an ongoing series on the usability characteristics of aged papers: stresses relationship of scientific tests to observations and use from librarian and conservator points of view.

Crock, D. M. and Bennett, W. E., *The Effect of Humidity and Temperature on the Physical Properties of Paper*. Surrey, The United Kingdom: British Paper and Board Industry Research Association, 1962. A still valuable comprehensive study of the effects of humidity and environment on a wide variety of papers.

Fellers, C., Iverson, T., Lindstrom, T., Nilson, T., and Rydahl, M., *Aging/Degradation — A Literature Survey*. Report Number 1E, FoU-projektet for papperskonservering, Stockholm, 1989. A recent review of the factors affecting paper aging and degradation. The first of a continuing series of excellent papers on these subjects.

Luner, P., *Wood Science Technology*, 22, 81 (1988). Evaluates paper permanence by several methods.

Sebera, D.K., "A Graphical Representation of the Relationship of Environmental Conditions to the Permanence of Hygroscopic Materials and Composites." In *Proceedings of Conservation in Archives: International Symposium, Ottawa, Canada, May 10-12, 1988*. Paris, France: International Council on Archives, 1989. An early exposition of the isoperm concept and its underlying principles and assumptions.

Sebera, D.K., "The Effects of Strengthening and Deacidification on Paper Permanence: Part 1— Some Fundamental Considerations." *Book and Paper Group Annual* 9: 65-117 (1990). Washington, DC: American Institute for Conservation.

Smith, R. D., *Library Quarterly*, 39, 153 (1969). An early, but still valuable introduction to the relationship of pH and environmental conditions to paper impermanence.